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Changes in dissolved organic matter with depth suggest the potential for postharvest organic matter retention to increase subsurface soil carbon pools

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ABSTRACT

Research into postharvest management of forests often focuses on balancing the need for increased biomass yield against factors that may directly impact the productivity of the subsequent stand (e.g. nutrient and water availability, soil microclimate, etc.). Postharvest organic matter management, however, also exerts a strong influence over the translocation of carbon (C) into and through the soil profile and may provide a mechanism to increase soil C content. The effects of contrasting postharvest organic matter retention treatments (bole-only removal, BO; whole-tree removal, WT) on soil solution C concentration and quality were quantified at the Fall River and Matlock Long-term Soil Productivity (LTSP) studies in Washington state. Solutions were collected monthly at depths of 20 and 100 cm and analyzed for dissolved organic C (DOC), dissolved organic nitrogen (DON) and DOC:DON ratio. Comparisons of DOC concentrations with depth illustrate divergent trends between the two treatments, with an overall decrease in DOC with depth in the BO treatment and either an increase or no change with depth in the WT treatment. Trends in DON concentrations with depth were less clear, partly due to the very low concentrations observed, although the relationship of DOC:DON with depth shows a decrease in the BO treatment and little to no change in DOC quality in the WT treatment. This illustrates that more recalcitrant organic matter (higher DOC:DON) is being removed from solution as it moves through the soil profile. Only 35–40% of the DOC moving past 20 cm in the BO treatment is present at 100 cm. Conversely, 98–117% of the DOC at 20 cm in the WT treatment is present at 100 cm. Thus, 11 and 30 kg C ha^{-1} yr^{-1} are removed from solution between 20 and 100 cm in the BO treatment at the Matlock and Fall River LTSP studies, respectively. Although much of this C is often assumed to be utilized for microbial respiration, DOC:DON ratios of the potential organic substrates and the unique mineralogy of the soils of this region suggest that a significant portion may in fact be incorporated into a more recalcitrant soil C pool. Thus, postharvest organic matter retention may provide a mechanism to increase soil C sequestration on these soils.

1. Introduction

In an introduction to a series of papers focused on the ecological aspects of dissolved organic matter (DOM) in soils, McDowell (2003) put forth a few key points regarding future direction and needs in DOM research. Among them are the needs to quantify the size of, and identify the controls over DOM sources and sinks, and to examine how these fluxes are altered in human-dominated environments. In general, these interests stem from the important role that DOM plays in many soil properties and processes. Chief among them are the regulation of the mobility of other elements and compounds, stability of soil colloids and aggregates, associated influence on nutrient cycling dynamics, and as a link between many different pools in the global carbon (C) cycle (Zsolnay, 2003). Thus, DOM exerts influence over terrestrial ecosystem functions that include biological productivity, water quality, and global change (Zsolnay, 2003). Investigating the role of forest management, and in this study specifically, postharvest organic matter management, on the sources, sinks, and controls over DOM, is an important step in understanding how such manipulations can influence the C cycle on pedon, landscape, and global scales.

General observations in forest soil organic matter dynamics suggest that litter and humus are the major sources of DOM and that subsurface mineral horizons serve as C sinks (Kalbitz et al.,

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2000; Kalbitz and Kaiser, 2008). Further, Kalbitz and Kaiser (2008) document the preferential removal of the more labile portions of DOM in soil O and A horizons, which results in more recalcitrant DOM leaching into soil subsurface horizons where this less bioavailable DOM is subject to sorption reactions with the mineral surface which further reduce their bioavailability (Guggenberger and Kaiser, 2003). Adding to this conceptual model, other studies have demonstrated that an increase in litter results in an increased flux of DOC into the soil (Park and Matzner, 2003; Fröberg et al., 2005). Thus, in the context of postharvest organic matter manipulations, it is plausible that with greater retention of postharvest residuals on-site, there would be an increased flux of recalcitrant C into the soil profile. The magnitude of this flux and ultimate fate of this C (e.g. leached from the profile, mineralized, or sorbed to mineral surfaces), dictates the potential for such management practices to increase soil C stocks.

The objective of this study was to assess the validity of such a model at two Long-term Soil Productivity (LTSP) studies in the Pacific Northwest US, each with contrasting organic matter retention treatments. This study focused on the depth relationships (20 and 100 cm) of dissolved organic C (DOC), dissolved organic nitrogen (DON), and DOC:DON collected in soil solutions. Our hypothesis was that increased organic matter retention on the soil surface would result in higher concentrations of DOC entering the subsoil which would be attenuated with depth due to both biotic and abiotic processes acting on the DOC. Following Bernal et al. (2005), we use DOC:DON as a proxy for the quality of the DOM, where increases in DOC:DON indicate reduced bioavailability. The resulting trends in DOC:DON with depth may help indicate the relative importance of abiotic and biotic factors influencing DOC dynamics.

2. Materials and methods

2.1. Study sites

This study utilized two affiliate sites of the USDA Forest Service LTSP research program (Powers et al., 1990): the Fall River and Matlock LTSP studies, located in western WA. Both sites are located in operationally managed stands predominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), with harvest and treatment installation occurring in 1999 and 2003 for Fall River and Matlock, respectively.

Soils and site productivities differ dramatically between the two sites. Soils of the Fall River LTSP study (46°43′N, 123°24′W) are of the Boistfort series (medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand) and are deep, well drained, silt loams to silty-clay loams that developed from Miocene basalt (Soil Survey Staff, 1999). Soils of the Matlock LTSP study (47°23′N, 123°43′W) are of the Grove series (sandy-skeletal, mixed, mesic Dystric Xerorthent) and are deep, well drained, very gravelly loamy sands formed in glacial outwash (Soil Survey Staff, 1988). As a result, these sites have contrasting productivity levels for Douglas-fir growth, with site indices (height at age 50 years; King, 1966) of 42 m at Fall River (Terry et al., 2001) and 36 m at Matlock (T.B. Harrington, unpublished data). Despite these differences, both sites have experienced volcanic ash deposition throughout their pedogenic histories. The influence of volcanic parent materials dominate the chemistry of soil profiles, particularly in the subsurface horizons, as demonstrated by Strahm and Harrison (2007, 2008).

A central focus of both the Fall River and Matlock LTSP studies is on the effects of postharvest management of woody debris and competing vegetation on soil processes and the productivity of the subsequent stand. A more detailed explanation of harvest, experimental design, and treatment installation and maintenance can be found in Ares et al. (2007) and Meehan (2006) for Fall River and Matlock, respectively. Within that context, this paper focuses on contrasting the conventional bole-only harvest (BO) treatment, and the most intensively harvested biomass removal treatment at each site, henceforth referred to as the whole-tree (WT) harvest. In the BO treatment, only tree boles up to an 8–13 cm top were removed from the treatment plots, with all remaining tops, broken logs <3 m in length, butt cuts, and remnant coarse woody debris left in place. The WT treatment at the Fall River LTSP study is referred to as the total-tree plus removal treatment (Ares et al., 2007), in which harvesting removed the entire aboveground tree biomass, including limbs and foliage. In addition, this treatment removed all remaining coarse wood debris (5–60 cm in diameter), including remnant decaying old-growth logs. The WT treatment at the Matlock LTSP study is known as the whole-tree removal treatment (Meehan, 2006), in which harvesting removed the entire aboveground tree biomass, including tops and limbs. It is worth noting that the designated WT treatment at Fall River represents a more intensive biomass removal than that of Matlock, due to the additional removal of the remnant woody debris, primarily legacy old-growth logs. There was much less old-growth legacy wood at Matlock compared to Fall River, thus by removing this material at Fall River the WT treatments may have become more comparable across sites. The forest floor was not removed at either location except for that which was inadvertently removed when legacy wood was removed. At Fall River and Matlock, harvest and treatment installation occurred during the springs of 1999 and 2003, respectively. For the purpose of this study, competing vegetation in both BO and WT treatments was controlled to eliminate confounding effects of understory vegetation response to the organic matter removal treatments, and its subsequent effects on soil C dynamics. This involved annual application of pre-emergent and post-emergent herbicides by backpack sprayer for a five-year period. Three additional herbicide treatments were applied selectively to reduce the abundance of Scotch broom (*Cytisus scoparius* (L.) Link) on all plots at the Matlock LTSP study.

2.2. Soil solution collection and analysis

Tension lysimeters (Cole, 1958) were used to collect soil solution at 20 and 100 cm depths in each replicate of the BO and WT treatments at the Fall River ($n = 8$) and Matlock ($n = 4$) LTSP studies. Collections occurred monthly for three full years at Fall River (August 2003–July 2006; years 5–7 following harvest and treatment installation) and for 21 months at Matlock (April 2005–December 2006; years 3 and 4 following harvest and treatment installation). Lysimeter design and installation for the Matlock LTSP study follows the description given specifically for those used at the Fall River LTSP study by Strahm et al. (2005). In general, tube lysimeters were constructed from PVC pipes and 0.1 MPa (1 bar), highflow, round-bottom, neck-top porous ceramic cups (Soilmoisture Equipment Company, Goleta, CA) with a maximum pore size of 2.5 mm and installed at an angle of 35° to minimize disturbance to the soil profile above the ceramic cups, and capped with a bentonite clay seal at the junction of the PVC tube and mineral soil surface to reduce preferential flow down the lysimeter tube. Monthly, a hand pump was used to apply a vacuum (−50 kPa) to each lysimeter. After a period of 7–10 days, soil solutions were collected and transported on ice back to the laboratory for analysis of DOC and DON within 24 h. The window of time between applying a vacuum and collecting solution represents a balance between the desire to collect sufficient solution for analysis and the risk of allowing the DOM to be biologically altered between the time it enters the lysimeter and is collected. DOC is measured as total organic C on a Shimadzu TOC-VCSH total organic C analyzer (Shimadzu Scientific Instruments, Columbia, MD) with a TNM-1N analyzer in series for the simultaneous determination of total N. DON is determined as the difference between total N and inorganic nitrogen, determined as nitrate and ammonium on an autoanalyzer (Perstorp Analytical 500 Series Flow-injection, Silver Spring, MD).

2.3. Data handling and statistics

Trends in DOC, DON, and DOC:DON with depth were analyzed across paired mean monthly 20 and 100 cm solution concentrations. These data only include points that represent the mean concentrations of two or more solution samples for any given depth by treatment by site combination. Given the regularity with which lysimeters fail to collect solution due to dry soils, vacuum leaks, etc., the total number of points in the data set is less than the total number of months that solution collections were made at each study site [Fall River: BO ($n = 27$), WT ($n = 30$); Matlock: BO ($n = 15$), WT ($n = 15$)].

Relationships in the data are represented visually through the use of geometric mean regression (GMR) lines and their confidence intervals, and statistically through the use of independent sample *t*-tests comparing means across treatments at each depth for each site (SPSS 16 for Mac, SPSS Inc., Chicago, IL). Given that both 20 and 100 cm lysimeter data are subject to mutual variability (Ricker, 1984), and the fact that in the presence of biological utilization of organic substrates, one can not be considered an appropriate predictor of the other, GMR analysis is a more appropriate tool to explore relationships in DOC, DON and DOC:DON between depths relative to least squares regression techniques (Clarke, 1980). Coefficients for slope, intercept, and the 90% confidence interval about the slope coefficients were computed as given by Ricker (1984) and Nigh (1995). Additionally, 90% confidence intervals about the mean of the 20 and 100 cm data were calculated and are expressed as an ellipse with its major axis equal to the slope of the GMR line (Ricker, 1984).

3. Results

3.1. Conceptual model

The relationship between the 20 and 100 cm lysimeter data illustrate the interactions of soil solution with soil solids and biota as C and N are transformed and translocated through the profile. A conceptual model of the soil solution depth relationships of DOC, DON, and DOC:DON for the BO and WT organic matter retention treatments is presented in Fig. 1. The 1:1 line represents no change in DOC or DON concentration, or DOC:DON between the two depths. Data falling above the 1:1 line indicate an increase in the concentration or ratio with depth, and suggests that the increase in the solution phase is a result of a loss from the solid phase (e.g. mineral soil, organic matter, etc.). Conversely, data falling below the 1:1 line indicate that the concentration or ratio in solution decreased with depth. This decrease in the solution phase is likely the result of either an increase in the solid phase, or C loss as evolved CO_2.

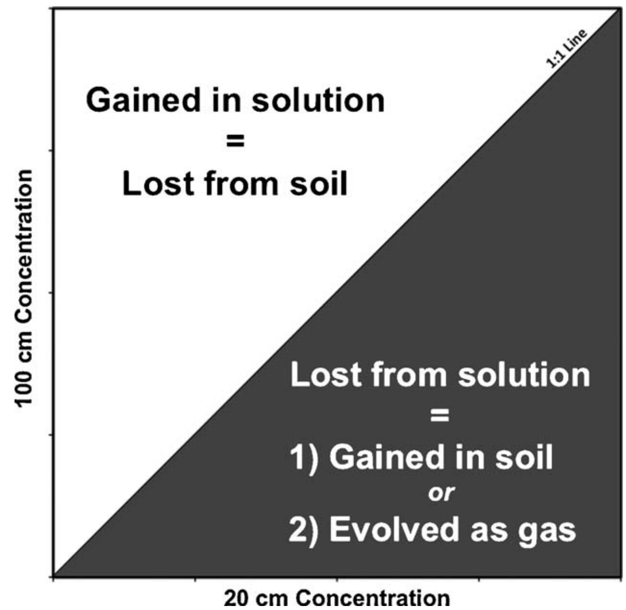

Fig. 1. Conceptual model illustrating the interactions of soil solutions with soil solids and biota as a function of depth, and the potential impacts on soil C pools. The 1:1 line represents no change in DOC or DON concentration, or DOC:DON with depth. Data falling above the 1:1 line indicate an increase in the concentration or ratio with depth, and suggests that the increase in the solution phase is a result of a loss from the solid phase (e.g. mineral soil, organic matter, etc.). Conversely, data falling below the 1:1 line indicate that the concentration or ratio in solution decreased with depth. This decrease in the solution phase is likely the result of either an increase in the solid phase, or C loss as evolved CO_2.

3.2. Dissolved organic C (DOC)

General trends in DOC with depth suggest an overall loss of C from solution with movement through the soil profile in the BO treatment at both the Fall River and Matlock LTSP studies (Fig. 2a and d), and either an increase (Fall River, Fig. 2a) or no change in DOC with depth (Matlock, Fig. 2d) in the WT treatment. Table 1 underscores these relationships, illustrating significant differences ($p \leq 0.001$) between BO and WT mean DOC concentrations at 20 cm for both sites. At 100 cm, however, there was no difference ($p \geq 0.35$) between the treatment means for DOC. This attenuation in DOC concentration at depth suggests that the C that was present at 20 cm has either sorbed to the soil surface, or was utilized for microbial respiration.

3.3. Dissolved organic N (DON)

Trends in DON concentrations with depth were less clear. DON at Fall River (Fig. 2b) illustrated little treatment effect, with no significant differences ($p \geq 0.45$) between the BO and WT treatments at either depth (Table 1). At Matlock, DON concentrations for the BO and WT treatments illustrate divergent trends with respect to depth (Fig. 2e), however, the mean concentrations are extremely low ($\bar{x} \leq 0.05\ \mathrm{mg\,N\,L^{-1}}$; Table 1) and neither 20 nor 100 cm DON solution concentrations were significantly different between the treatments ($p \geq 0.24$).

3.4. DOC:DON

Given the rather low DON concentrations, trends in DOC:DON appear to largely be driven by DOC concentrations themselves. In all but one case, DOC:DON ratios decreased with depth (Fig. 2c and f). The GMR line for DOC:DON for the WT treatment at Fall River falls on the 1:1 line, indicating no change in the DOC:DON with depth in that treatment. Table 1 also shows significant differences ($p \leq 0.01$) in DOC:DON ratios at 20 cm, which are attenuated at 100 cm. As a proxy for the C:N ratio of the organic matter in solution, it is noteworthy that the lowest mean DOC:DON ratio is 153, and lowest 90% confidence interval of a DOC:DON ratio is 118 (Table 1), considerably higher than a C:N of 20, below which is commonly considered a readily utilizable C substrate for microbial respiration (Myrold, 2005).

4. Discussion

DOC itself can make up a substantial proportion of the soil C pool (Neff and Asner, 2001), contributing up to 50% of the total soil

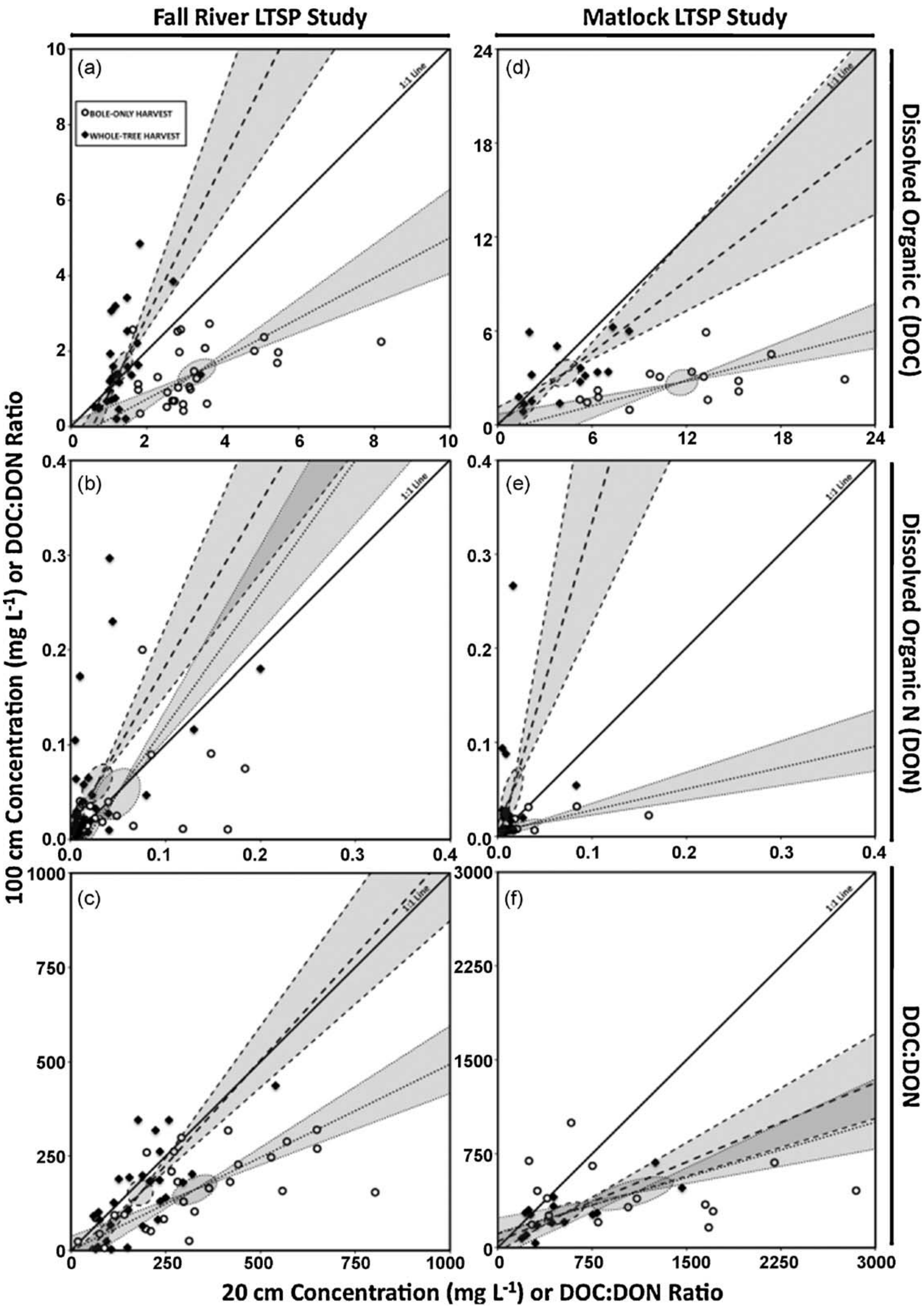

Fig. 2. Relationships of dissolved organic C (DOC; a and d), dissolved organic N (DON; b and e), and DOC:DON (c and f) between 20 and 100 cm lysimeters for the bole-only (BO, open circles) and whole-tree (WT, closed diamonds) treatments of the Fall River (left column) and Matlock (right column) LTSP studies. Geometric mean regression lines, 90% confidence intervals of the slope of the line, and 90% confidence ellipses about the mean of the data set are given for each treatment where lines for BO are dashed and WT are dotted.

C in some cases (Kalbitz and Kaiser, 2008). DOC fluxes out of soils are often small, particularly when compared to soil C pools and other terrestrial ecosystem C fluxes, such as primary productivity and heterotrophic respiration (Kalbitz and Kaiser, 2008). Further, DOC concentrations deep in soil profiles are almost universally observed to be lower than concentrations in upper horizons, irrespective of vegetative cover or current land use (Qualls and Haines, 1991; Currie et al., 1996; Dosskey and Bertsch, 1997; Kalbitz et al., 2000; Neff and Asner, 2001; Fröberg et al., 2007). According to Kaiser and Guggenberger (2000), DOM that enters the

Table 1
Means and 90% confidence intervals (CI) for dissolved organic C (DOC, mg L^{-1}), dissolved organic N (DON, mg L^{-1}), and DOC:DON for each site by treatment by depth combination. Levels of significance are the result of a two-sample *t*-test between the treatments for each row.

			Bole-only		Whole-tree		*p*
			Mean	90% CI	Mean	90% CI	
Fall River	20 cm	DOC	3.32	2.87–3.77	1.35	1.18–1.53	<0.001
LTSP		DON	0.05	0.03–0.07	0.03	0.02–0.04	0.449
Study		DOC:DON	326	263–389	184	152–215	0.010
	100 cm	DOC	1.43	1.19–1.67	1.59	1.23–1.95	0.347
		DON	0.05	0.02–0.08	0.02	0.04–0.08	0.973
		DOC:DON	161	130–192	153	118–188	0.312
Matlock	20 cm	DOC	11.62	9.57–13.7	4.26	3.25–5.26	0.001
LTSP		DON	0.03	0.01–0.05	0.01	0.01–0.02	0.260
Study		DOC:DON	1070	730–1400	524	360–688	0.006
	100 cm	DOC	2.72	2.18–3.27	3.32	2.55–4.08	0.781
		DON	0.01	0.01–0.02	0.05	0.02–0.07	0.236
		DOC:DON	433	334–532	272	203–341	0.865

soil profile and does not leach out has two primary fates: *in situ* stabilization or mineralization. Thus, changes in soil C stocks largely depend on the balance of these two potential endpoints for DOM.

As a proxy for the C:N ratio of DOM, and thus the ease of microbial utilization for respiration, DOC:DON can serve as a useful indicator for the mineralization potential of DOM. Thus, high DOC:DON substrates may be less likely to be used for respiration than low DOC:DON substrates. This rationale only holds, however, when the microbial community is N-limited, and thus scavenges N (including DON) in order to mineralize C. Although this was not assessed directly in this study, Jones et al. (2008) suggest that low DOC:DON ratios would be an indication of a potential C-limitation rather than an N-limitation of the microbial community. Surprisingly, the DOC:DON reported in this study are an order of magnitude higher than those reported in the literature. Mean soil solution DOC:DON values reported from various depths beneath differing cover types were all below 45, including studies in agricultural systems (Vinther et al., 2006), deciduous forests (Michalzik et al., 2001; Solinger et al., 2001; Currie et al., 1996), coniferous forests (Michalzik et al., 2001; Currie et al., 1996), and even a stream draining an oak-pine woodland (Bernal et al., 2005). Following the rationale of Jones et al. (2008), stated above, our data indirectly suggest that the microbial communities acting upon DOM in these systems are indeed N-limited, and by extension, that DOC:DON may be a useful indicator of DOM bioavailability. While it is possible that the observed DOC:DON in this study is a result of sugars or other high C:N, yet highly labile organic substrates, Guggenberger and Zech (1994) illustrated that carbohydrates made up a relatively small proportion of leachates beneath two intact Norway spruce (*Picea abies*) stands, and proposed that most of the remaining DOC was composed of lignin-degradation products which are inherently more recalcitrant. Considering the elevated lignin content of postharvest residues relative to typical litter fall, it seems reasonable that the solutions collected in this study may also be low in carbohydrates relative to solubilized lignin-degradation products. Given that the C:N of live and dead branches for both dominant overstory species prior to harvest [Douglas-fir and western hemlock (*Tsuga heterophylla*)] ranged from 200–600 (Ares et al., 2007), it also seems reasonable, in the BO treatment at least, that much of the DOM is a product of residual material left after harvest. Mechanisms for elevated DOC:DON in the WT treatment are less clear, given that the complete harvest removal of the aboveground vegetation did not add high C:N material to the soil surface. Chen et al. (2001), however, reported C:N of two size classes of Douglas-fir and western hemlock roots ranging from 187 to 313, which may contribute to the observed DOC:DON in both treatments observed. Coupled with a general increase in soil temperature with this treatment at Fall River specifically (Devine and Harrington, 2007), it seems likely that mineralized root biomass is the primary contribution to these observations. Although soil solutions integrate all of the potential sources of DOC above or adjacent to their point of collection, it was not possible in this study to quantify differential contributions of roots, forest floor and harvest residuals.

In a review of the controls on the dynamics of dissolved organic matter, Kalbitz et al. (2000) state that although litter is one of the most important sources of DOM in soils, the effect of changes in litter quantity and quality on DOM is not clear. We believe that this study clearly illustrates the potential for postharvest organic matter retention to increase the DOC flux to subsurface mineral soil horizons. In the case of the BO treatment at Fall River, it appears that the DOC may also be in a form, based on DOC:DON characteristics, that would be less readily utilized by a presumably N-limited microbial community. The potential impact that this has on soil C stocks following such forest management practices is dependent on the fate of that added DOC. Given the nearly universal decrease in concentration with depth, two primary fates are possible: sorption or mineralization. Prevailing theories regarding DOM dynamics in general are that a large portion of the newly added C will be sorbed to soil solids and preserved through the decreased bioavailability of such compounds (Kaiser and Guggenberger, 2000; Kalbitz et al., 2000; Guggenberger and Kaiser, 2003). Studies from these sites specifically (Strahm and Harrison, 2007, 2008) reinforce this notion by demonstrating a sorption capacity for nutrient anions and organic acids in these subsurface soils that exceeds a number of other soils more traditionally considered to exhibit such characteristics. Further, Strahm and Harrison (2008) demonstrate that for the subsurface soils at Fall River, the sorption of highly labile organic acids subsequently reduced the mobility and bioavailability of the substrates. Coupled with the observed trends in DOC concentration and DOC:DON, this suggests that the balance of these two potential outcomes may tend toward abiotic sorption of DOC to soil solids in favor of biotic utilization of the C substrates.

5. Conclusions

Pairing the DOC concentrations presented here with site specific soil–water balance estimates based on the model detailed by Strahm et al. (2005) in an earlier N leaching study at Fall River allowed for the estimation of soluble C flux through the soil profile. Based on these leaching estimates, only 35–40% of the DOC moving past 20 cm in the BO treatment is present at 100 cm. Conversely, 98–117% of the DOC at 20 cm in the WT treatment is present at 100 cm. Thus, 11 and 30 kg C ha^{-1} yr^{-1} are removed from solution in the BO treatment from the Matlock and Fall River LTSP studies, respectively, between the depths of 20 and 100 cm. Although much of this C is often assumed to be utilized for microbial respiration, the shift in DOC:DON, coupled with the demonstrated potential of the soils on these sites to contribute to the sorptive preservation of DOM (Strahm and Harrison, 2008), suggests that a significant portion may in fact be incorporated into the more recalcitrant soil C pool. Thus, postharvest organic matter retention may provide a mechanism to increase soil C sequestration on these soils. Planned future work characterizing soil C pools at these sites (at ten-year intervals from study initiation through rotation age) should provide the opportunity to assess the validity of the potential for postharvest organic matter retention to increase subsurface soil C content by integrating over longer time scales the soil C dynamics inferred by the shorter term observations made in this study.

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